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III. THE FLUX OF GALACTIC HEAVY PRIMARIES ON GEMINI VII

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JOINT REPORT

DEPARTMENT OF THE NAVY · NAVAL AEROSPACE MEDICAL INSTITUTE

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SUMMARY PAGE

THE PROBLEM

Nuclear emulsions flown in small packs within the space suits of the astronauts on the 14-day mission Gemini VII so far have been evaluated only for the proton dose accumulated in passes through the South Atlantic Anomaly. As preliminary information, this seemed satisfactory because theoretical assessment indicated that the contribution from galactic heavy nuclei would remain on the level of a few per cent of the total exposure. This report presents the results of a semi-quantitative method of assessing the heavy flux in the emulsions by visual comparison of track appearance under the microscope with a standard scale of nuclei of known Z numbers.

FINDINGS

Since identification of very heavy nuclei by the indicated method is more reliable than for medium heavy and light nuclei, the microscope scanning was limited to nuclei of $Z \geq 20$. A total of 287 different track segments were counted, yielding a total mission flux of 38.4 nuclei/cm^2 of $Z \geq 20$. The corresponding tissue dose from this flux equals 1.35 millirads. The theoretical value for the incident flux, based on the best available data on the heavy spectrum and the geomagnetic latitude profile of the Gemini VII mission, equals 74.8 nuclei/cm^2. If a collision mean free path of 14 g/cm^2 for nuclei of $Z \geq 20$ is assumed, a quantitative assessment of the shielding effect using the shield distribution analysis communicated by McDonnell Aircraft Corporation leads to a residual flux of 43 per cent of the incident flux. Experimental and theoretical values thus appear to match surprisingly well. The results confirm earlier estimates which had indicated a dose from heavy nuclei of $Z = 3$ to 28, on a Gemini type orbit, of less than 5 per cent of the total exposure. To be sure, this statement applies only to the absorbed dose. The radiobiological problem of special "microbeam" effects of heavy nuclei and their adequate dosimetric assessment is not a part of this study.

INTRODUCTION

In two earlier reports (1, 2), hereafter referred to as Reports 33 and 38, the results of nuclear emulsion scans on Gemini missions IV and V (Report 33) and on mission VII (Report 38) have been presented. In this earlier work the evaluation effort was limited essentially to the populations of protons in the emulsions. In line with the established fact that the bulk of the radiation exposure on a Gemini type orbit is due to trapped protons in the South Atlantic Anomaly, this limitation was entirely acceptable. The dose contribution of the heavy component of galactic radiation was only roughly estimated from existing data on the fluxes and energy spectra of heavy primaries in the literature which lead to an estimated dose contribution of less than 5 per cent of the proton dose.

Because of the great disparity in frequency, only very few heavy nuclei are accumulated by the time statistically significant data on the proton population are obtained in the process of microscopic evaluation. Scanning for heavy nuclei, therefore, requires entirely different provisions concerning magnification and sweep lines, making it a task of its own that has to be separated completely from the proton scan. The following report presents the results of such a separate evaluation carried out on one G.5 emulsion sheet flown on the left chest of the pilot on the 14-day mission Gemini VII.

GEOMAGNETIC CUT-OFF EFFECTS ON THE HEAVY GALACTIC FLUX ON GEMINI TYPE ORBITS

Accurate determination of the Atomic Number Z from a nuclear emulsion track requires large emulsion volumes which allow a nucleus to travel a considerable length and to come to the end of its ionization range in emulsion. For a single emulsion pair of one 200 micra G.5 and one K.2 emulsion, each 1 x 1-1/2 inches in size, as used in the space suits of the Gemini astronauts, fulfillment of this requirement was entirely out of reach. In such small emulsion volumes merely an estimate of the Z number of a track is possible. This can be effected only by comparing characteristic visual features of a track, mainly the delta ray aura and the diameter of the solid silver core, to those of tracks of known Z found, for instance, in the classical atlas of Powell, Fowler, and Perkins (3). Since such estimates are bound to carry a certain margin of error, it seems desirable to compare them with the theoretical flux that can be established from the orbital parameters of the mission and from existing data on the heavy component of galactic radiation. We shall derive this theoretical flux first.

Gemini VII was launched on 4 December 1965 into an orbit of 28.9°-inclination with a perigee of 100 and an apogee of 204 statute miles. It re-entered on 18 December 1965 after completion of 220 orbits and 330.6 hours in orbit. If the orbital inclination of 28.9° toward the plane of the geographic equator is to be expressed in geomagnetic terms, the following elementary facts about the relation of the two coordinate systems involved should be remembered. The axis of the magnetic dipole field of the Earth does not coincide with the axis of rotation; the two axes form an angle of 11.5°. Due to the rotation of the Earth in absolute space, the axis of an inclined satellite orbit, remaining fixed in absolute space once it is established, continuously rotates about the rotational axis of the Earth as seen from the latter's reference system. As a consequence, the geomagnetic inclination of a satellite orbit oscillates continuously between the values of its geographic inclination minus 11.5° and plus 11.5°. This variation, in turn, causes the integral galactic flux accumulated by the satellite per orbit also to change continuously because the sweep of geomagnetic inclinations is different for each individual orbit. This influence is very pronounced because the galactic flux very strongly depends on geomagnetic latitude. The so-called minimum momentum of arrival for a cosmic ray particle approaching the Earth from interplanetary space varies with the fourth power of the cosine of geomagnetic latitude. Therefore, continuously varying flux fractions are cut off from the integral flux that reaches the vehicle as its geomagnetic latitude changes. Various analytical expressions have been proposed in the literature for the dependence of the integral galactic flux on cut-off momentum or cut-off energy. In the following analysis, the spectral model as proposed by Waddington (4) has been used.

For a mission of 220 orbits, the geomagnetic inclination passes many times through the complete cycle from 29° - 11.5° to 29° + 11.5°. This circumstance makes a numerical evaluation of the varying flux contributions from orbit to orbit dispensable by allowing computation of the grand total mission flux by taking the weighted mean over the full sweep of all orbital inclinations. A brief outline of the basic steps of the computation is presented in the Mathematical Appendix. The results lead to a mean geomagnetic latitude of 23° for the Gemini VII mission in the sense that the integral heavy flux at 23° multiplied by the mission time of 330.6 hours furnishes the correct grand total integral mission flux.

In the context of the present investigation, interest centers on the dose contribution from galactic heavy nuclei. However, it should be remembered that this dose actually constitutes part of a total exposure which is by more than 95 per cent due to trapped protons. In regard to a resolution of the Z spectrum of the two contributions, this circumstance creates a different situation from that of the earlier studies in Reports 33 and 38. As pointed out there, the method of determining absorbed energy by track and grain count does not require identification of the Atomic Number Z of a charged particle that has produced a track. Obviously, two track segments of the same length, one from an alpha particle of higher energy and the other one from a proton of lower energy that shows the same LET, i.e., the same grain count, represent identical contributions to the absorbed energy, i.e., to the dose. In this sense the "proton" doses reported in the earlier studies contain a certain undetermined fraction from heavier nuclei such as alpha particles and possibly even nuclei up to Li (Z = 3) or Be (Z = 4). From general information on the radiation environment in space, it is known that for a Gemini type orbit, the dose fraction from all heavy components of galactic radiation, as compared with the dose from trapped protons, does not even reach the 5 per cent level. It seemed acceptable, therefore, to disregard what precise fraction of the 5 per cent from heavy nuclei is actually contained in the result of the scan and to call that result simply the "proton" dose. However, as we are setting out now to assess the small dose contribution from all non-proton particles more accurately, the undetermined fraction of it already contained in the "proton" dose assumes a completely different importance which requires closer examination.

Taking up alpha particles first, we remember that they as well as all other heavy nuclei in the radiation environment in space are exclusively of galactic origin and therefore are subjected to the geomagnetic cut-off limitations for charged particles in the magnetosphere of the Earth. At the medium and low latitudes of a Gemini orbit, the cut-off effect completely excludes low energy particles from reaching the Earth. For alpha particles in particular, this means that the LET spectrum is limited to values which allow grain counts throughout the entire spectrum. In other words, the full contribution of the alpha component is included in the "proton" dose. The corresponding LET spectra for still heavier nuclei up to Be ($Z = 4$) might contain also certain fractions of grain countable tracks. However, as the so-called L nuclei in Waddington's terminology, i.e., nuclei of $Z = 3$ to 5, are known to show very low abundances in the galactic spectrum, the undetermined dose fraction from these nuclei contained in the "proton" dose cannot be very high. Therefore, an upper limit approach of adding in full the assessed dose from all components heavier than alpha particles to the "proton" dose seems acceptable though it would mean that the unidentified fraction from lithium and beryllium nuclei ($Z = 3$ and 4) is entered twice into the grand total. This overrating of actual exposure would seem more of a safeguard than an objection in the context of an investigation where the issue at stake is radiation safety of personnel.

Whereas the flux data on galactic alpha particles from various sources, on which Waddington's spectral formula is based, are in good agreement, information on abundances of the heavier components is more limited. In the present analysis, the H-nuclei in Waddington's classification, i.e., nuclei with a Z number of 10 and higher, are of special interest. Their energy or rigidity spectra are generally assumed to show the same basic configuration as alpha particles, with merely the flux constants being different. For the flux ratio H/alpha in particular, Waddington uses the value 0.022 as the best compromise between results of different observers. He further divides the H class into two subgroups $Z = 10$ to 19 and $Z \geq 20$ and quotes 0.37 as the best value for the ratio $(Z = 20)/(Z = 10$ to $19)$. From these data, one arrives at the value 0.006 for the ratio of the $Z \geq 20$ group to alpha particles. Since we have limited, for reasons explained in the next section, the heavy count to nuclei of $Z \geq 20$, the just-quoted value for their relative abundance is of special interest for a critical comparison of our experimental flux value with the theoretical one. With the latitude sweeps of the Gemini VII orbits taken into consideration (see Mathematical Appendix), the value 0.006 leads, for a horizontal target area of 1 cm^2 and 2 pi incidence, to a flux of 5.35 traversals of nuclei $Z \geq 20$ per day or 74.8 nuclei for the entire mission of 14 days.

Since we are interested ultimately in absorbed tissue dosages on the bodies of the astronauts at the location of the emulsion packets, the flux values for the various Z groups of the heavy galactic spectrum just arrived at theoretically should be expressed also in absorbed doses. The energy spectra of the galactic components remain confined to relativistic and near-relativistic values because of the low geomagnetic latitudes to which the orbits of the mission remained confined. As shown before, the highest geomagnetic latitude that can occur on any orbit of the mission equals 40.5°. This corresponds to a minimum kinetic energy of arrival of 494 Mev/nucleon for nuclei with A = 2 Z. By reference to protons of 494 Mev, one sees that at this energy, the LET is only 1.35 times larger than its minimum value. Applying this value, which actually holds only for the flux fraction at the low energy end of the E spectrum, to the entire flux will overrate slightly the actual dose. However, the computation is greatly simplified with this approximation since pertinent LET values can now be obtained directly from the LET of protons by applying the Z^2 relationship.

Table I

Theoretical Fluxes* and Tissue Dose Rates* of Galactic Heavy Nuclei for Effective Mean Geomagnetic Latitude of Gemini VII Mission

Group of Elements	Z Numbers	Flux, Particles/ (m^2 sec ster)	Dose Rate, millirads/24 hrs	Mission Dose, millirads
Li, Be, B	3, 4, 5	0.59	0.023	0.32
C, N, O, F	6, 7, 8, 9	2.14	0.28	3.99
Ne to K	10 to 19	0.537	0.185	2.59
Ca to Ni	20 to 28	0.20	0.19	2.60
		Total heavy dose not accounted for in grain count analysis:		9.50

*Fluxes are computed from integral rigidity spectra proposed by Waddington (4). Dose rates are computed assuming 2 pi incidence and no shielding.

Table I shows the results of the calculation. The last two columns present the 24-hour and the total mission doses, respectively. Listed are only the components of the heavy spectrum from Z = 3 on up. As explained before, the component Z = 2, i.e., alpha particles, with its contribution to the tissue dose, can be assumed to be fully contained in the "proton" dose since all galactic alpha particles furnish grain countable tracks. The theoretical value of the alpha dose as it follows from Waddington's spectrum equals 0.32 millirad/24 hrs or 4.42 millirads for 14 days. This is indeed a very small fraction of the "proton" dose of 200 millirads obtained from track and grain counting and shown in Report 38. A comparison of the total contribution of 9.5 millirads from the heavy spectrum from Z = 3 to 28 as listed in Table I with the just-quoted dose of 200 millirads from protons and alpha particles confirms the earlier estimates that the dose from galactic particles not accounted for in the grain count analysis remains on the level of 5 per cent of the total exposure. To be sure, this statement is valid only as long as absorbed doses expressed in conventional dosimetric units of millirads are compared. If the question of the "microbeam" effectiveness of heavy nuclei and their adequate dosimetric assessment is raised, the dose values listed in Table I assume quite a different meaning. However, these aspects are beyond the scope of this treatise.

It was already mentioned that the actual microscopic scan for heavy nuclei was limited to the heaviest group of $Z \geq 20$. Since, for this group, the mean free path for nuclear collision is comparatively short, the intrinsic shielding of the vehicle frame and equipment of the Gemini ship as well as self-shielding of the bodies of the astronauts can be expected to produce a sizeable attenuation. It seems of interest to attempt a quantitative estimate of the residual flux for the $Z \geq 20$ group.

A very elaborate blueprint analysis of the shield distribution of the Gemini vehicle has been carried out by Chappell and collaborators at McDonnell Aircraft Corporation (5). The particular set of data from that study which best fits the present purpose is the one for what was termed as Reference Point II, i.e., the testes of the right-hand astronaut. The set gives the resulting slant thicknesses including self-shielding due to the astronauts' bodies for 720 directions of the full 4-pi solid angle. Table II is a greatly condensed version of the original data which suffices for the present purpose.

The mean free path for nuclei of $Z \geq 20$ is needed for assessing the attenuation due to nuclear collision. As a compromise of somewhat divergent values of different observers, we have selected the value 14 g/cm^2. Column 3 in Table II lists the pertinent exponential terms, exp (-d/14), and Column 4 the contribution to the residual flux, i.e., the product of the exponential factor and the fractional solid angle. It is seen that the total residual flux reaches only 44 per cent of the incident flux.

In the foregoing assessment of the shielding effect deep space conditions are assumed, i.e., 4 pi incidence, whereas 2 pi geometry prevailed on the Gemini VII mission since the planetary body of the Earth blacked out the entire lower hemisphere. Under these conditions the effective instantaneous shielding changes continuously, depending on the attitude of the vehicle. A quantitative analysis would require complete records on the attitude throughout the mission. Such a detailed study is not intended here. The finding that the inherent shielding for a random attitude would attenuate the $Z \geq 20$ flux to about half its incident value seems sufficient as a general estimate.

EXPERIMENTAL PROCEDURES

If one compares the available data of authors (6, 7) who have attempted to determine abundances of individual Z numbers in the H class ($Z \geq 10$) of the galactic spectrum, one discovers general agreement on the fact that the Atomic Numbers 16,

Table II

Slant Thicknesses Including Self-Shielding Due to Astronauts' Bodies at Right-Hand Crewman's Testes in Gemini Vehicle*

Slant Thickness d, g/cm^2	Fraction F of 4 pi	Resid. Flux, exp (-d/14)#	F x exp (-d/14)
24.4	0.43	0.175	0.07342
22.0	0.04	0.208	0.00833
19.5	0.01	0.248	0.00248
17.1	0.05	0.295	0.01475
14.7	0.03	0.351	0.01054
12.2	0.02	0.418	0.00836
9.77	0.06	0.498	0.02987
7.32	0.02	0.593	0.01185
5.86	0.03	0.658	0.01974
4.88	0.02	0.706	0.01411
4.39	0.02	0.731	0.01461
3.91	0.01	0.757	0.00757
3.42	0.08	0.783	0.06267
2.93	0.04	0.811	0.03245
2.44	0.02	0.840	0.01680
1.95	0.01	0.870	0.00870
1.47	0.05	0.901	0.04504
0.977	0.04	0.933	0.03730
0.488	0.02	0.966	0.01931
TOTAL:	1.00		0.43790 or ~44% of incident flux

*Data of D. A. Chappell and collaborators, see Reference (5).

#A collision mean free path of 14 g/cm^2 is assumed for heavy nuclei of $Z \geq 20$.

17, 18, and 19 (the elements S, Cl, Ar, and K) show markedly lower abundances than the elements immediately preceding and following in the Periodic System. One would expect, then, in a line-up of the continuum of tracks of increasing Z under the microscope, a certain gap setting apart tracks of $Z \leq 15$ from those of $Z \geq 20$. Obviously, this circumstance could be utilized in the scanning procedure by limiting the count to the group of $Z \geq 20$. In the scan for heavy nuclei which is reported here we have attempted to apply the indicated criterion. That means we have limited the scan to tracks of the heaviest group ($Z \geq 20$), selecting in the well-known line-up of relativistic tracks of all Z numbers in the atlas of Powell, Fowler, and Perkins (l.c., 3) the track for $Z = 20$ as the minimum track to be accepted in the scan. Admittedly, this method is rather crude and carries a large margin of error, possibly as high as ± 2 units in the Z number. However, the coarse estimate obtained by assessing the flux for a component that accounts only for a few per cent of the total exposure would still seem of interest since such an estimate constitutes the only possibility of extracting at least some semi-quantitative information on the galactic exposure from the very small emulsion volumes that could be accommodated in the radiation packs to be worn by the astronauts in their space suits.

The micrographs of Figures 1 and 2 demonstrate the basic criteria which were used in counting the track population of $Z = 20$ and higher. Micrograph Figure 1 shows a rare coincidence of three heavy nuclei almost intersecting each other. In comparing them carefully to the standard scale of Powell, Fowler, and Perkins we estimate their Z numbers as in the range of 8 to 12, with the track running from NNE to SSW as the lightest and the one running from NNW to SSE as the heaviest. In other words, these three tracks represent heavy nuclei which were rejected as too light in the count. In contradistinction, micrograph Figure 2 shows a heavy track which is estimated at $Z = 20$. In other words, this track just meets the specifications.

It should be mentioned that the entire count of 287 identified tracks of $Z \geq 20$ was carried out by one observer (Sullivan) who commands an experience of several years with track identification. A special problem in identifying Z numbers by visual comparison is posed by tracks with steep dip angles. Due to projective image compression in the the longitudinal direction, such tracks appear heavier and their Z numbers are easily overestimated. We have tried to allow for this phenomenon by requiring an increasingly heavier appearance for increasingly steeper angles. A certain test of how well we succeeded in this compensation of the dip angle effect can be established by analyzing the dip angle distribution of the total population of accepted tracks. For isotropic 2 pi incidence the frequency distribution of the angles at which particles arrive and intersect a horizontal target area depends on the sin cos product of the angle of incidence. This theoretical distribution is shown as a smooth curve in Figure 3. The histogram in the same figure shows the actual distribution of 287 counted tracks, divided into nine classes of 10°-width zenith angle each. It is seen that there is indeed a trend toward overrating Z numbers of tracks for steepening dip angles. Again, as this overrating of Z numbers constitutes an overrating of flux and dose, we did not attempt a correction since a conservatively high estimate is desirable.

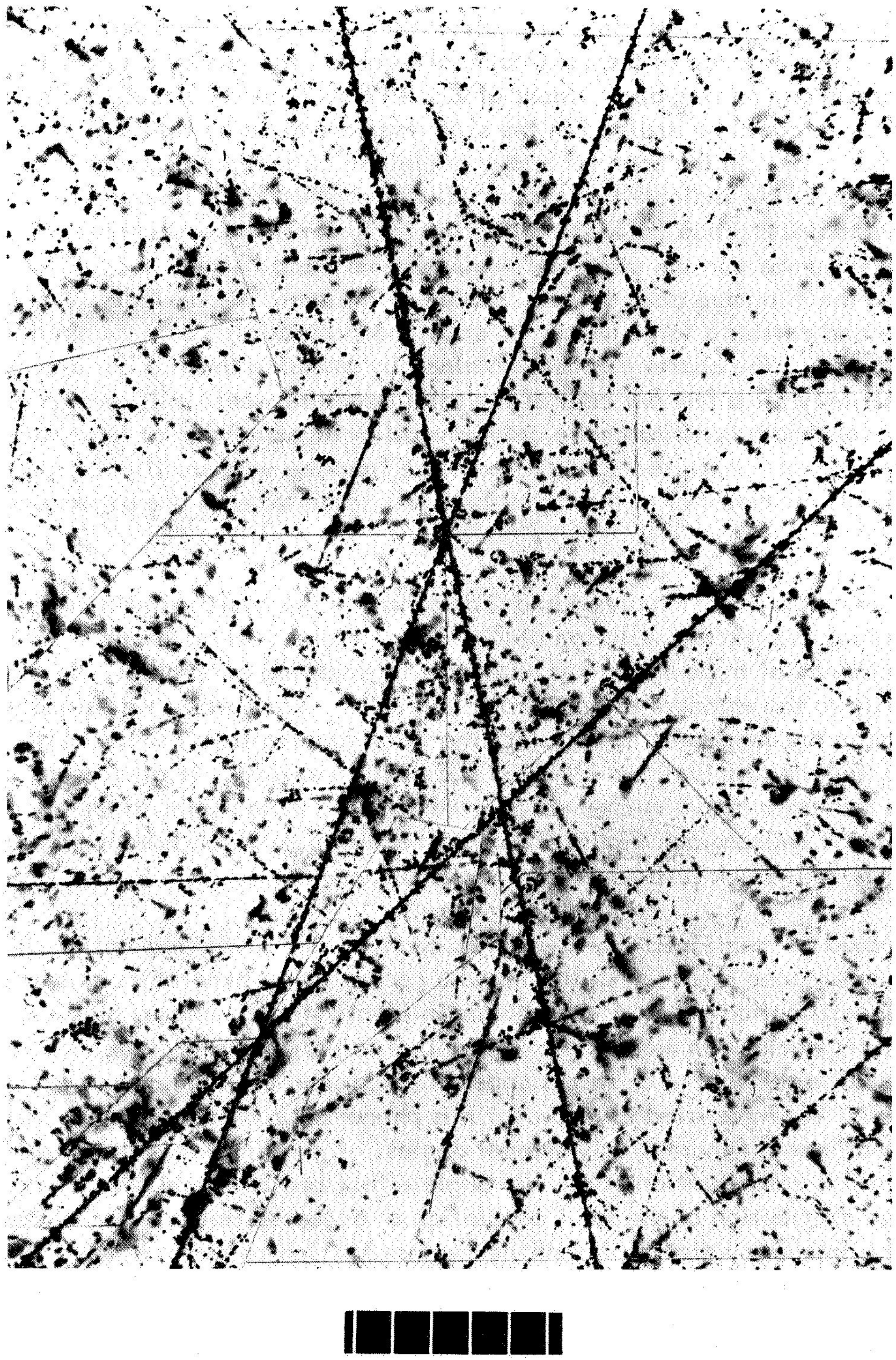

Figure 1

Composite Micrograph of 200 micra G.5 Emulsion Sheet Showing Rare Coincidence of Three Heavy Tracks of Estimated Z Numbers 8 to 12

1 Scale Division = 10 micra

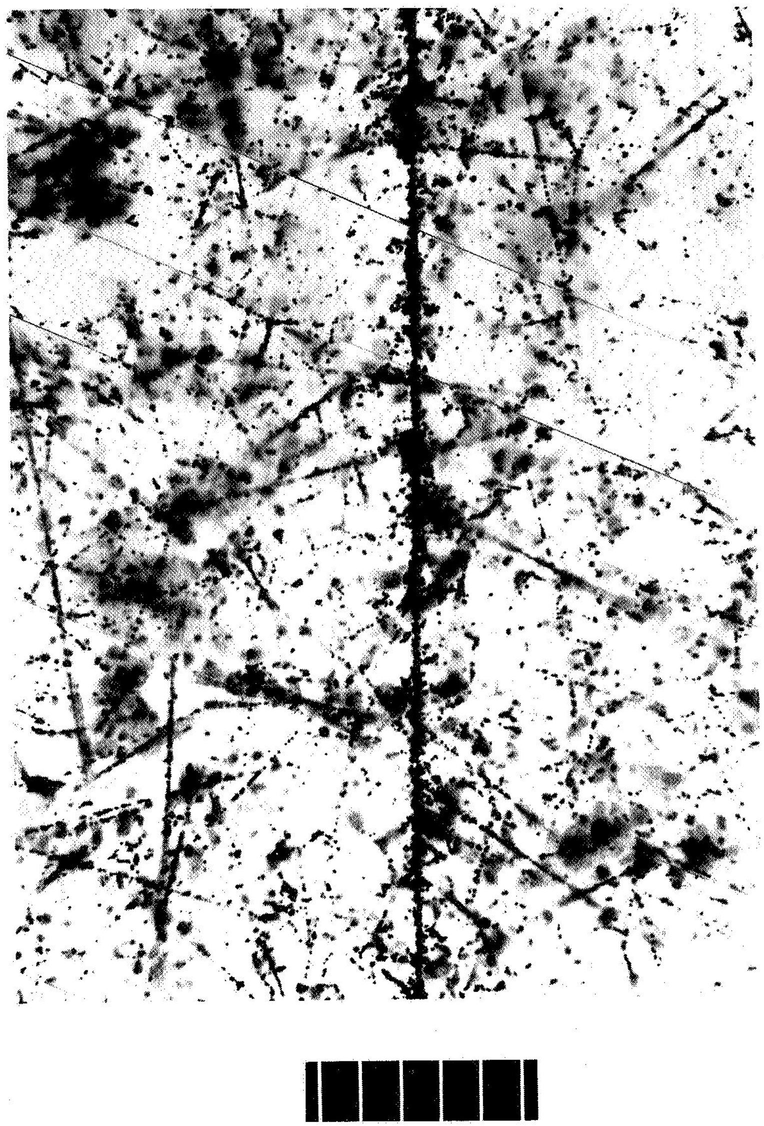

Figure 2

Composite Micrograph of 200 micra G.5 Emulsion Sheet Showing Track of Estimated Z = 20

1 Scale Division = 10 micra

Focal planes of mosaic sections in Figures 1 and 2 are always adjusted to heavy tracks and therefore change discontinuously at some seams, especially in Figure 1 where all three heavy tracks have different angles of tilt to emulsion plane.

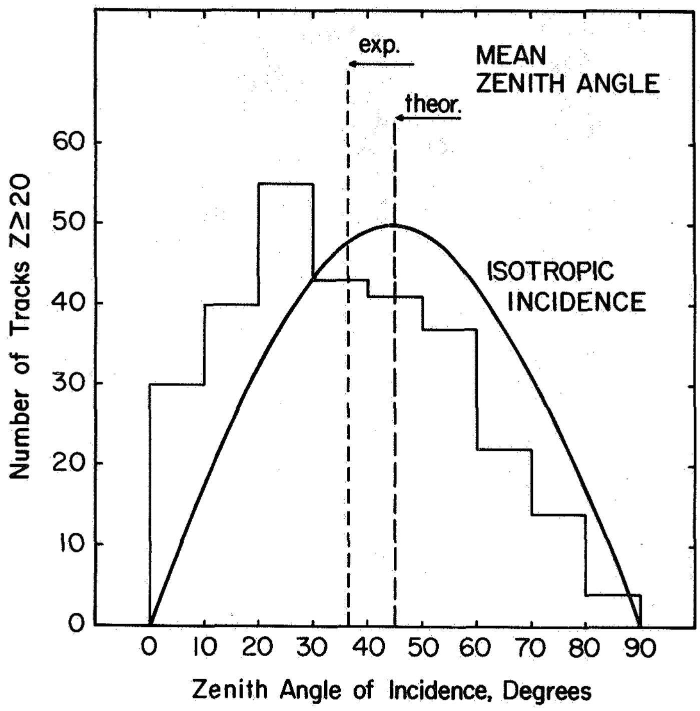

Figure 3

Zenith Angle Distribution in Horizontal Target Area for Isotropic Incidence (Curve) and for 287 Observed Tracks of $Z \geq 20$ (Histogram)

The result of the scan, expressed in terms of traversals of a target area of 1 cm^2 from all directions for nuclei of $Z \geq 20$, is 38.4 nuclei/cm^2. This value compares with a theoretical flux of 74.8 nuclei/cm^2 as derived in the preceding section. As also shown there, the inherent shielding of the vehicle and the self-shielding of the astronauts' bodies can be expected to attenuate an incident flux of $Z \geq 20$ nuclei to about 50 per cent. It is seen, then, that the agreement between theory and experiment is surprisingly good. In fact, we consider this close agreement fortuitous and due to some unidentified error compensation since the undeterminacies involved in both the theoretical assessment and the experimental procedure are much larger than the difference of a few per cent between the computed and observed value. We should also like to point out that our experimental value of 2.74 nuclei/cm^2 per day for $Z \geq 20$ is in close agreement with the value of 3.0 tracks/cm^2 per day found by Benton and Collver (8) on Gemini VI .

Using the flux value as found in the scan, one obtains a dose contribution of half the value listed in Table I for the $Z \geq 20$ group. It should be noted that the same factor of 0.5 cannot be applied to the dose contributions of the three other groups of nuclei in Table I. Because the values for the mean free paths of collision for these lighter nuclei are larger, the resulting attenuation can be expected to be smaller. Nevertheless, the substantial reduction of the dose contribution from the $Z \geq 20$ group due to shielding, in conjunction with the unknown smaller corresponding reductions for the three other groups, indicates that the figure of 5 per cent used throughout this report as the estimated dose contribution from galactic heavy nuclei is conservatively high.

DISCUSSION

As far as the radiation burden of the astronaut is concerned, the main result of the present study is the confirmation of earlier estimates which assessed the contribution from heavy components not contained in the grain count analysis at less than 5 per cent of the combined proton and alpha dose. The present evaluation also shows that the dose from alpha particles, in turn, constitutes about another 5 per cent of the total exposure, leaving 90 per cent contributed by trapped protons in the South Atlantic Anomaly. Again, we should like to emphasize that this conclusion pertains to absorbed doses expressed in millirads. The complex issue of appropriate QF factors for heavy nuclei will not be taken up in this study.

A final question not directly connected to the main topic of this report concerns the contribution from beta and gamma rays. Unavoidably, manned space missions require longer lead times for the preparation of the radiation packs. Although both the nucleonic as well as the beta and gamma components contribute to the background exposure of the emulsions, they do so in a basically different way. In the sea level background the contribution from nucleonic components is substantially smaller than that from beta and gamma rays. For the radiation environment in orbit, the situation is exactly reversed. As a consequence, the beta and gamma exposure accumulated during some six to eight weeks at sea level before development of the emulsions is markedly greater than the corresponding exposure in space, whereas the opposite is true for the nucleonic components. A separate determination of the fraction of the beta and gamma exposure accumulated in orbit, therefore, is quite difficult. Nevertheless, the emulsions flown on Gemini VII indicate that the in-space exposure from beta and gamma rays constitutes only a small fraction of the corresponding exposure accumulated at sea level. To this point, we submit Figure 4, showing a micrograph at lower magnification of the same visual field as Figure 1 which allows for a better judgment of the background in general. Finally, Figure 5 presents a micrograph taken directly from a G.5 emulsion of the sea level controls. It shows a few protons of very high energy, one of them centrally traversing the entire field. This particular proton has a grain count of 45 grains/100 micra, placing it in the energy range of 250 Mev. Main attention, however, is directed to the characteristic tortuous blobs from terminating electrons. While a quantitative comparison of respective blob frequencies in Figure 5 and Figure 1 is a more involved procedure requiring direct observation at the microscope, a perfunctory inspection of the micrographs suggests that these two frequencies differ merely by a small margin. The exposure excess from beta rays in space, therefore, appears to be small, certainly smaller than the 5 per cent contribution to the total dose from galactic heavy nuclei.

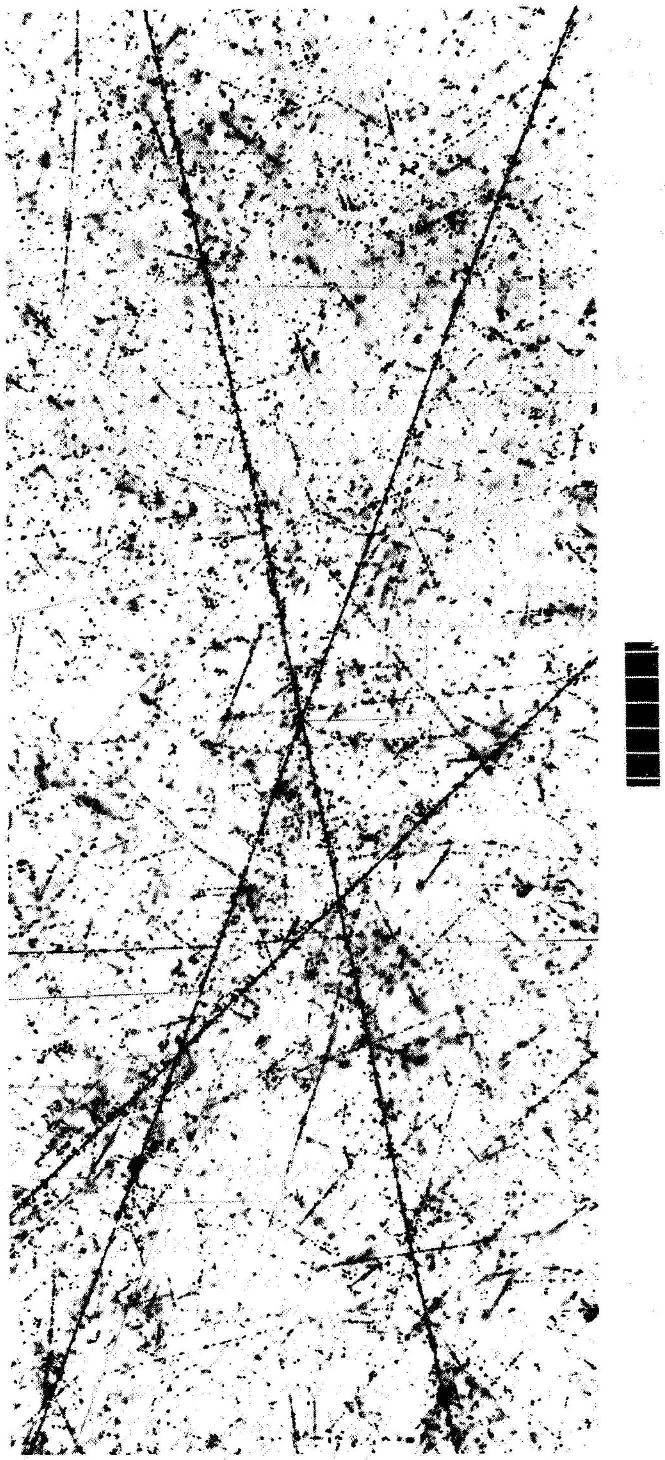

Figure 4

Composite Micrograph of Triplet of Heavy Tracks of Figure 1
Shown at Lower Magnification

1 Scale Division = 10 micra

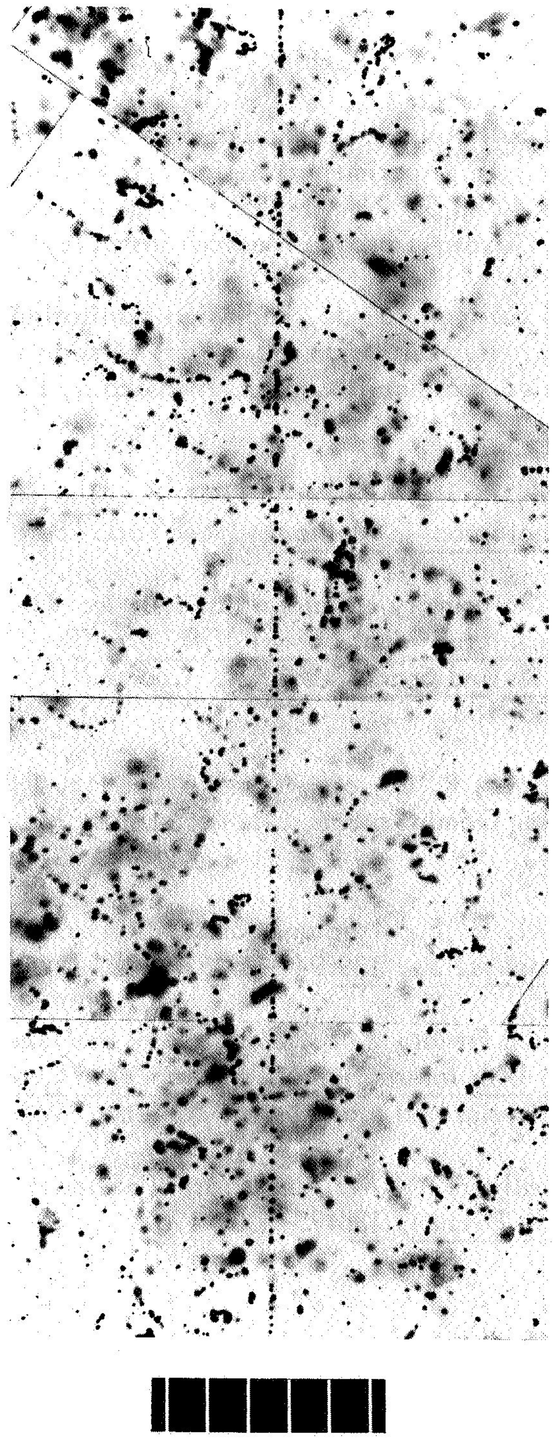

Figure 5

Composite Micrograph of 200 micra G.5 Emulsion Sheet Kept as Sea Level Control

1 Scale Division = 10 micra

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MATHEMATICAL APPENDIX

The basic relationships between the geographic and the geomagnetic coordinate system of the planet Earth have been outlined by Singer.* The geomagnetic pole in the Northern Hemisphere is located at longitude 70° W and latitude 78.5° N. The geomagnetic latitude, L, on any location with the geographic longitude, G, and the geographic latitude, H, is obtained from the equation:

$$\text{Sin } L = \cos 78.5° \cos H \cos (G-70) + \sin 78.5° \sin H. \qquad (1)$$

The geographic inclination of a satellite's plane of orbit does not change as long as no power maneuvers are executed. The rotation of the Earth merely changes the particular longitude at which the maximum latitudinal elongations North and South occur. This means that, in Equation (1), the geographic latitude of the instantaneous position of the satellite sweeps, on each and every orbit, through the interval from 29° S (i.e., $H = -29°$) through zero to 29° N (i.e., $H = +29°$) and back to 29° S if the actual inclination of the Gemini VII orbit of 28.9° is rounded off to 29°. Since $\cos(-H) = \cos H$ and $\cos 29° = 0.87462$, we see that the factor cos H in Equation (1) sweeps four times through the interval from 0.87462 to 1.00000 for a full orbit. At the same time, the geographic longitude sweeps, for every full orbit, through a full cycle of 360°, with the cosine completing a full cycle from +1 to zero to -1 to zero. Since the Earth rotates underneath the revolving satellite, the two periodicities, that of the instantaneous geographic latitude of satellite position and that of its longitude, show a continuously changing phase relation in the sense that, if a certain latitude coincides with a certain longitude on one orbit, the same latitude will coincide, on the following orbit, with a more westward longitude. For a revolving time of 90 minutes, this westward phase shift equals 22.5° per orbit because $1.5/24 = 22.5/360$. As a consequence, the amplitude of variation of geomagnetic latitude varies from orbit to orbit, oscillating itself between a maximum amplitude of 29° + 11.5° and a minimum of 29° - 11.5°. It is seen by inspection that the two extreme values occur when the orbital axis lies in one plane with the geographic and geomagnetic axes, i.e., when the respective poles of the three axes on the Earth's surface lie on one great circle. Inclination is minimum when the geomagnetic and the orbital axes are on the same side of the geographic axis and is maximum when they are on opposite sides. While the variation of the geomagnetic inclination of orbit remains confined to the interval between the two extremes of 29° - 11.5° and 29° + 11.5°, i.e., never becomes zero, the instantaneous geomagnetic latitude of position passes through zero twice on every orbit, because any two great circles on a sphere (in this case the satellite orbit and the geomagnetic equator) intersect twice.

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*Singer, S. F., The primary cosmic radiation and its time variations. In: Wilson, J. G., and Wouthuysen, S. A. (Eds.), Progress in Cosmic Ray Physics. Vol. IV. New York: Interscience Publishers, 1958. Pp 205-335.

For a mission like Gemini VII with 220 orbits it is an acceptable approximation to assume that the geomagnetic inclination of orbit carries out an integer number of full sweeps between its extreme values. This proposition simplifies numerical operations substantially since one no longer has to follow through individual orbits, but can establish the flux for selected inclinations suitably spaced over the full range of possible values. The total flux for a full sweep can then be established easily by numerical integration, and the grand total flux for the mission is obtained by adjusting to 220 orbits.

In proceeding to the evaluation of the flux, we remember first that the minimum momentum of arrival, M, for a particle of unit charge approaching the Earth from interplanetary space is related to geomagnetic latitude by the equation $M = 14.9 \cos^4 L$ where M is obtained in units of Gev/c. For nuclei of multiple charge, M is to be interpreted as momentum per unit charge which is also called magnetic rigidity. With this information, any rigidity spectrum can be evaluated in terms of the total flux accumulated on an orbital mission of known geomagnetic sweep.

For galactic heavy nuclei, the rigidity spectrum of the alpha component has been especially well investigated. The corresponding spectra for the heavier components of Z = 3 to 28 are usually directly linked to the alpha spectrum by using the same basic formula with appropriately reduced flux constants. In the present investigation, the integral rigidity spectrum for galactic alpha particles as proposed by Waddington (ref. 4, main text) has been used. After establishing the geomagnetic sweep for all possible orbits, weighing their respective frequencies of occurrence in the total of 220 orbits, the flux accumulated on each orbit was computed by numerical integration by breaking down the 360° of a full revolution into 6°-intervals and determining, for the mean geomagnetic latitude of each interval, the flux increment. As a result of this computation, one obtains a mean flux of 32.88 alpha particles/(m^2 sec ster) which corresponds to a mean rigidity or a mean minimum momentum of arrival per unit charge of 10.68 Gev/C or, finally, to a mean kinetic energy of 4.48 Gev/nucleon. Consulting again Waddington's paper (ref. 4, main text) for data on relative Z abundances, one finds, as the best compromise between reported values, the value of 0.00594 or $\sim$ 0.006 for the ratio of nuclei of $Z \geq 20$ to alpha particles. Applying this ratio to the just-quoted absolute flux of the alpha component leads to a mean flux for $Z \geq 20$ nuclei of 0.197 nuclei/(m^2 sec ster). Assuming 2 pi incidence and a horizontal target area of 1 cm^2, one obtains a flux of 5.35 nuclei/(cm^2 24 hrs) and a total flux of 74.8 nuclei/cm^2 for the 14-day mission.

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13. ABSTRACT

Earlier evaluations of small nuclear emulsion sheets flown on the astronauts' bodies during the 14-day Gemini VII mission had been limited to grey tracks which allowed grain counting. This report provides data on the population of heavy tracks. By comparing visual appearance of the diameter of the solid silver core and of the delta ray aura with tracks of known Z, tracks of $Z \geq 20$ were identified and counted. A total of 287 such tracks yielded a mission flux of 38.4 nuclei/cm^2 of $Z \geq 20$, corresponding to a tissue dose of 1.35 millirads. Theoretical assessment of the flux by considering the geomagnetic latitude profile of the mission leads to 74.8 nuclei/cm^2 of $Z \geq 20$. The difference closely matches the expected attenuation due to the inherent shielding of the vehicle and the self-shielding of the astronauts' bodies if one assumes a collision mean free path of 14 g/cm^2 for nuclei of $Z \geq 20$. The results confirm earlier estimates that galactic heavy nuclei contribute less than 5 per cent to the total absorbed dose.

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